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Applied Thermal Engineering 23 (2003) 1407–1415

APPLIED THERMAL ENGINEERING

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Electrical performance of skutterudites solar thermoelectric generators

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Received 12 September 2002; accepted 6 March 2003

Abstract

The paper focuses on the electrical performance of skutterudites based solar thermoelectric generators (STG). Basics of STG mathematical modeling are reported. Two STG concepts, namely the flat plate model with identical collector and radiator areas and the STG configuration with concentrators have been considered. Their performance is assessed for different solar intensities. The idea is to understand how such systems would perform if they were on board a spacecraft on journey towards the Sun.

Keywords: Thermoelectric devices; Thermoelectric energy conversion; Skutterudites; Computational model

1. Introduction

These last years, considerable efforts have been developed to identify new classes of thermoelectric materials with enhanced performances compared to established thermoelectric materials [1,2]. Among materials prospected, $CoSb_3$ based-skutterudites appear as very promising because of their attractive thermoelectric properties [3]. N- and p-type materials have been synthesized and were found to have thermoelectric performances substantially larger than those of the established Si–Ge based alloys, making them very attractive in a variety of applications in the field of space and waste heat recovery. The development of segmented thermoelectric unicouples using advanced thermoelectric materials, whose skutterudites, is currently under investigation [4,5]. This

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1359-4311/03/$ - see front matter
doi:10.1016/S1359-4311(03)00065-6

Nomenclature

A	cross-section area of the thermoelectric legs (m^2)
A_{TE}	area of the thermopiles (m^2)
h_1	thickness of the collector (m)
h_2	thickness of the radiator (m)
I	electrical current (A)
j	density of electrical current (A/m^2)
K_1	collector area/thermopiles area
K_2	radiator area/thermopiles area
l	height of the thermoelectric legs (m)
q	heat flux (W/m^2)
q_a	heat flux absorbed from the Sun by the collector surface (W/m^2)
q_c	heat flux at the cold thermoelement junction (W/m^2)
q_e	heat flux radiated to space by the collector surface (W/m^2)
q_h	heat flux at the hot thermoelement junction (W/m^2)
q_i	heat flux conducted through the insulation (W/m^2)
q_r	heat flux radiated to space by the radiator surface (W/m^2)
r_c	contact resistance (Ωm^2)
R_1	specific heat resistance of the collector (m K/W)
R_2	specific heat resistance of the radiator (m K/W)
STG	solar thermoelectric generator
T	temperature (K)
T_1	temperature of the collector (K)
T_2	temperature of the hot side of the thermopile (K)
T_3	temperature of the cold side of the thermopile (K)
T_4	temperature of the radiator (K)
W	output power of the STG (W)
x	distance from the cold junction (m)

Greek symbols

α	Seebeck coefficient (V/K)
η	efficiency of the STG
$\varkappa$	thermal conductivity (W/m K)
σ	electrical conductivity ($\Omega^{-1}\,m^{-1}$)

Subscripts

n	n type thermoelectric material
p	p type thermoelectric material

new unicouple has an experimental efficiency value on the order of 10% when operating over a 300–873 K temperature difference with a projected thermal to electrical efficiency of up to 15% for a hot side temperature of 1000 K [5].

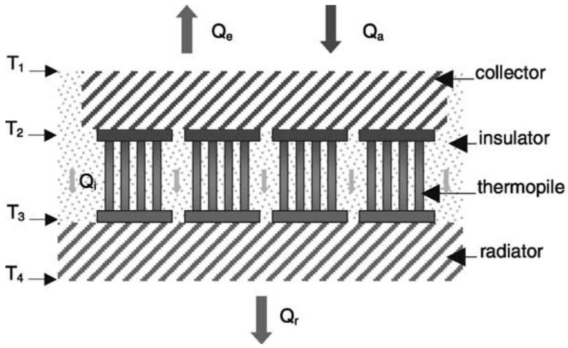

Fig. 1. The principle scheme of a flat plate STG.

Recently, we proposed to incorporate the skutterudite materials in solar thermoelectric generators (STG) to replace conventional solar cells for near Sun missions [6]. In order to evaluate the performances, dimensions and weight characteristics of different STG concepts, we developed a powerful mathematical model based on the optimal control theory [7]. The analysis has been performed especially for a STG operating at 0.45 A.U. from the Sun and for 400 W electrical output requirements. Basically, a STG consists of a collector, the thermopiles, an insulation and a radiator (Fig. 1). The thermopile is constituted of several thermocouples connected electrically in series and thermally in parallel. Each thermopile is totally encapsulated within an electrical insulator. This approach has many advantages. For example, the thermopiles can be connected in parallel, thereby providing an overall reliability.

To extract all the relevant STG parameters, different materials have been selected for their specific physical properties: skutterudite materials for the thermoelectric part, low thermal conductivity material of commercial grade from Microtherm for the insulating parts and aluminium nitride (AlN) for both the collector and the radiator. Two concepts have proven to be potentially attractive for space missions near the Sun: the flat plate model with identical collector and radiator areas (Fig. 1) and the STG configuration with a single solar concentrator or mini-solar concentrators for each thermopile unit, in place of the flat-plate collector. It has been shown in [6] that it is possible with these two concepts to reach specific power values higher than 13 W/kg for working surfaces as low as 1.5–2.4 m^2.

In this paper we propose to extend the work presented in [6] and particularly to study in depth the electrical performance of the STG as a function of Sun–spacecraft distance. The study is conducted on two previously [6] optimized STG concepts for a distance of 0.45 A.U., for 400 W electrical output power and for a required load voltage of 30 Vdc. The physical equations necessary to solve this problem are reported in the next section.

2. Physical analysis

The performance of the "off-design" STG i.e. at different Sun–spacecraft distances is estimated from the energy balance equations that were used for the design of the optimized STG by the mathematical theory of optimal control [6,7]. The system of equations to be solved is:

$$q_a - q_e = \frac{1}{R_1 h_1}(T_1 - T_2) \tag{1}$$

$$q_r = \frac{1}{R_2 h_2}(T_3 - T_4) \tag{2}$$

$$q_a K_1 - q_e K_1 - q_h(T_2, T_3) - q_i(K_2 - 1) = 0 \tag{3}$$

$$q_r K_2 - q_i(K_2 - 1) - q_c(T_2, T_3) = 0 \tag{4}$$

where T_1 and T_4 are the temperatures of the collector and the radiator and T_2 and T_3 the temperatures of the hot and the cold sides of the thermopile (see Fig. 1). For the set of equations (1)–(4) q_a, q_e, q_r and q_i represent the densities of heat absorbed from the Sun by the collector plate, radiated to space by the collector and by the radiator surfaces and, conducted through the insulation, respectively. The expressions of these heat densities are detailed in [6]. Their values are highly dependent on the incident solar heat flux and on the physical properties of the collector, the radiator and the insulation materials. For the "off-design" model, the ratios of the collector and the radiator areas to the thermopiles area K_1 and K_2, the specific heat resistances of the collector and the radiator materials R_1 and R_2 and their thicknesses h_1 and h_2 have been considered as initial data for this problem and their values correspond to their optimal values obtained in the design mode.

The heat flux at the hot and cold junctions of the thermoelements, q_h and q_c, are calculated using the system of differential equations for the temperature and the heat flux distribution within the n- and p-legs of the thermocouple at a distance x from the cold junction given by:

$$\left.\begin{aligned} \frac{dT}{dx} &= -\frac{\alpha j}{\varkappa}T - \frac{q}{\varkappa} \\ \frac{dq}{dx} &= \frac{\alpha^2 j^2}{\varkappa}T + \frac{\alpha j}{\varkappa}q + \frac{j^2}{\sigma} \end{aligned}\right\}_{\mathrm{n,p}} \tag{5}$$

where α, σ, $\varkappa$ are the temperature dependent Seebeck coefficient, the electrical and the thermal conductivities, respectively, $j_{\mathrm{n,p}} = I/A_{\mathrm{n,p}}$ are the electrical current densities inside n- and p-legs respectively and $A_{\mathrm{n,p}}$ are the cross-sections areas of the legs.

Under the following boundary conditions:

$$T_n(0) = T_p(0) = T_3, \quad T_n(l) = T_p(l) = T_2 \tag{6}$$

solution of Eq. (5) at any given value of current I through the thermoelement gives the opportunity to calculate the heat densities q_h and q_c at the hot and cold thermoelement junctions using the expressions:

$$\begin{aligned} q_h &= -\sum_{n,p}[q(l) + j^2 r_c] \\ q_c &= -\sum_{n,p}[q(0) - j^2 r_c] \end{aligned} \tag{7}$$

where r_c is the contact resistance and l is the thermoelement legs height. According to experimental investigations developed on electrical contact resistances with skutterudites [4], we assumed $r_c = 5 \times 10^{-10}\ \Omega\mathrm{m}^2$.

If the temperatures $T_1, \ldots, T_4$ and the heat flux q_h, and q_c—satisfying the energy balance equations (1)–(4) at any given electric current I—have been determined, the "off-design" STG output power W and the efficiency η can be calculated by the following relationships:

$$W = A_{TE}(q_h - q_c) \tag{8}$$

$$\eta = \frac{q_h - q_c}{q_h} \tag{9}$$

where A_{TE} is the area of the thermopiles.

The load current and the load voltage can be easily found using the current value I through the thermoelement, the number of thermocouples per thermopile, the number of thermopiles per STG and the information about their electrical connection [6].

The set of equations (1)–(9) forms the basis for the algorithm and computer program for the estimation of the electrical performance of the STG under the off-design conditions.

To detail the description of the computational model, it should be mentioned that the four unknown temperatures T_1–T_4 are extracted from the system of energy balance equations (1)–(4) using the Newton iteration method. Simultaneously, inside each iteration the heat densities q_c and q_h are estimated from the combination of the Euler method and the shooting method for the numerical solution of the differential equations (5) and (6). During the calculation process, the current I is varied to find its optimal value regarding on the required conditions: peak power output or fixed load voltage.

3. Results and discussion

Detailed theoretical simulation has been carried out to determine the performances, dimensions and weight characteristics of different STG designs based on advanced skutterudite materials [6]. These designs have been optimized for operation at a distance of 0.45 A.U. from the Sun, and for 400 W requirements. Three STG concepts have been proposed and investigated. In the first concept, the collector and the radiator plates have been assumed to have identical areas ($K_1 = K_2$). It is a so-called flat-plate STG (Fig. 1). The second one is a STG having the radiator plate area larger than the collector plate area ($K_2 > K_1$). The third concept is an STG with a single solar concentrator or with mini-solar concentrators for each thermopile, in place of the flat-plate collector. In this case K_1 is interpreted as a concentration ratio (usually $K_1 > K_2$). From the obtained results [6], it appeared that the flat plate configuration with the lowest area (concept I) and the configuration with solar concentrator with maximum value of concentration coefficient (concept III with $K_1 = 55$) were the most suited according to our selection criteria (low mass, high specific power). These two concepts have been selected for the investigation of the STG performances under the "off-design" conditions. Detailed performance characteristics of these two STG concepts designed to provide 400 W at 30 Vdc at a distance of 0.45 A.U. under a perpendicular solar flux are listed in Table 1. It should be noted that the STG performances are only dependent on the total area of the thermoelectric material. Neither its division into thermoelements and thermopiles nor their electrical connections have an influence on the output power and the

Table 1
Performances of two STG concepts designed for 400 W requirement at 0.45 A.U. under 30 Vdc following the model developed in [6]

	Flat-plate STG	STG with solar concentrator
Concentration coefficient	–	55
STG total area (m^2)	2.4	1.3
Total area of thermopiles (m^2)	6.8×10^{-2}	5.1×10^{-2}
Thermoelement length (m)	1.0×10^{-2}	1.0×10^{-2}
Number of thermocouples	539	454
n-type leg cross-section area (m^2)	5.64×10^{-5}	5.16×10^{-5}
p-type leg cross-section area (m^2)	7.06×10^{-5}	6.14×10^{-5}
Mass of thermoelectric material (kg)	5.2	3.9
Power per unit area (W/m^2)	167	312
STG hot-side temperature (K)	838	926
Radiator temperature (K)	543	606
Total heat transmitted (kW)	9.23	7.75
Load voltage (V)	30	30
Load current (A)	13.3	13.3
Conversion efficiency (%)	5.2	5.8

efficiency. Therefore, it has been assumed for simplicity that the thermocouples in the "reference" design STG are not divided into thermopiles and are connected electrically in series.

Based on these results and using the mathematical model developed in the previous section, we analyze how the electrical performances of the two selected STG depend on the incident solar heat flux. It is interesting to know at which distance from the Sun how much electrical power can theoretically be produced by a STG. Moreover, since the orbit of some planets is eccentric (for example the orbit of Mercury around the Sun ranges between 0.31 and 0.47 A.U.), it is also of interest to have information about the thermal conditions imposed to the STG as a function of the Sun–spacecraft distance changes. Actually, the skutterudite material performance degrades when its temperature becomes greater than 1000 K.

Tables 2 and 3 show the dependence of the key electrical parameters upon Sun–spacecraft distance for the flat-plate STG concept and for the STG with solar concentrator, respectively, assuming an incident perpendicular solar flux. It is quite obvious that the solar flux (solar constant) and consequently the heat transmitted through the thermopiles, the temperatures of the collector and the radiator and the output power are basically dependent on the distance from the Sun. It is seen that in both concepts, the STG can deliver 30 Vdc only from 0.6 A.U. from the Sun. For this distance, the output power is around 100 W. When the distance is smaller than 0.45 A.U. output powers higher than 400 W can be delivered. If the spacecraft moves to 0.30 A.U. the collector temperature increases up to 1000 K for the two selected concepts, and the power available at 30 Vdc reaches 1 kW. This value represents an increase of 150% relative to the "reference" design. This large excess of electrical power can be used advantageously to provide power for battery for example or can be reduced to a lower level thanks to the electrical subsystem. The results of Tables 2 and 3 allow also to determine the electrical performances of the two "reference" design generators as a function of generator tilt angle. Actually, if the STG is at a given distance from the sun and is tilted so that the incident flux is less than the solar constant at

Table 2
Flat plate STG performance as a function of its distance from the Sun

Distance from Sun (A.U.)	Solar constant (kW/m^2)	Voltage (V)	Peak power output (W)	Power output at 30 Vdc (W)	Collector temperature (K)	Radiator temperature (K)	Efficiency (%)	Total heat transmitted (kW)
1.00	1.37	6.5	24		478	390	1.2	2.4
		30.0		–				
0.80	2.14	10.5	57		560	430	2.0	3.5
		30.0		–				
0.70	2.80	14.0	94		616	455	2.6	4.5
		30.0		–				
0.60	3.80	18.5	160		687	485	3.4	5.8
		30.0		98	699	482	2.2	5.6
0.50	5.48	25.3	290		780	521	4.5	7.8
		30.0		280	785	519	4.5	7.7
0.45	6.77	30.0	400		838	542	5.2	9.2
0.40	8.56	30.0		556	902	567	5.9	11.3
		36.0	573		906	567	6.2	11.1
0.35	11.2	30.0		754	976	603	6.2	14.2
		45.0	840		987	597	7.2	13.8
0.30	15.2	30.0		1011	1066	646	6.1	18.8
		55.0	1271		1082	636	8.2	17.9

Table 3
Performance of STG with solar concentrator as a function of its distance from the Sun

Distance from Sun (A.U.)	Voltage (V)	Peak power output (W)	Power output at 30 V (W)	Hot side temperature (K)	Radiator temperature (K)	Efficiency (%)	Total heat transmitted (kW)
1.00	8.0	34		561	447	1.8	2.2
	30.0		–				
0.80	12.0	72		648	489	2.6	3.2
	30.0		–				
0.70	15.0	111		705	514	3.3	3.9
	30.0		–				
0.60	19.0	177		777	545	4.1	5.0
	30.0		121	788	539	3.0	4.7
0.50	25.0	301		869	583	5.2	6.6
	30.0		291	873	580	5.2	6.5
0.45	30.0	400		926	606	5.8	7.7
0.40	30.0		544	988	637	6.4	9.5
	35.0	554		992	634	6.7	9.3
0.35	30.0		721	1062	676	6.5	12.1
	42.0	782		1069	668	7.5	11.6
0.30	30.0		948	1150	728	6.3	16.3
	51.0	1140		1162	714	8.1	15.3

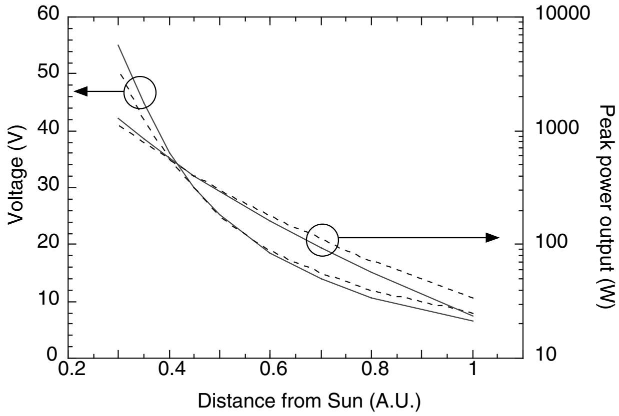

Fig. 2. Influence of the spacecraft–Sun distance on the peak-power output and voltage for the flat plate STG (straight lines) and the STG with solar concentrator (dashed lines).

that distance, a new effective distance corresponding to the actual heat flux at the generator may be obtained. Note that tilting the STG can be also an efficient way to decrease the excess of power if necessary when the Sun–spacecraft distance approaches 0.30 A.U.

As a result of the larger temperature gradient across the thermoelements, the efficiency increases with decreasing Sun–spacecraft distance. For the flat-plate STG design, the temperature reached, even at a distance as low as 0.30 A.U., does not exceed the allowable temperature range of the skutterudite thermoelectric materials. For the STG concept with the solar concentrator it will take place for distances below 0.35 A.U. Therefore, no particular action is needed to limit temperature increase. If the distance becomes smaller than 0.30 A.U. or 0.35 A.U., the flat-plate STG or the solar concentrator STG, respectively, cannot be used without being tilted with respect to the Sun or shielded.

The dependences on the distance from the Sun of peak power output and voltage at peak power for the two STG concepts are shown in Fig. 2. The peak power represents the power obtained when the load resistance is fixed to its optimal value. It can be seen from Fig. 2 that both parameters increase when the spacecraft approaches the Sun. Moreover, the performances of both STG concepts considered are not significantly distinguished. By varying the load resistance, one can provide output powers of the order of 100 W at 15 Vdc from 0.70 A.U. and reach about 1.2 kW at 50 Vdc for a distance closer to the Sun.

4. Conclusion

The paper has emphasized the performance of two STG concepts. It turned out that the typical power requirements on board of a spacecraft equipped with such systems can be easily fulfilled. For solar distances smaller than 0.45 A.U. but not lower that 0.30 A.U., power in excess of 400 W can be generated by a flat plate STG without constraining the spacecraft design. Below 0.30 A.U., tilting of the flat plate STG would maintain the temperatures within the allowable range.

Acknowledgement

This work was supported by ESTEC/ESA, contract no. 15071/01/NL/PA.

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